

The eRHIC Science Case

BNL eRHIC Review
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a passion for discovery



U.S. DEPARTMENT OF
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The charge

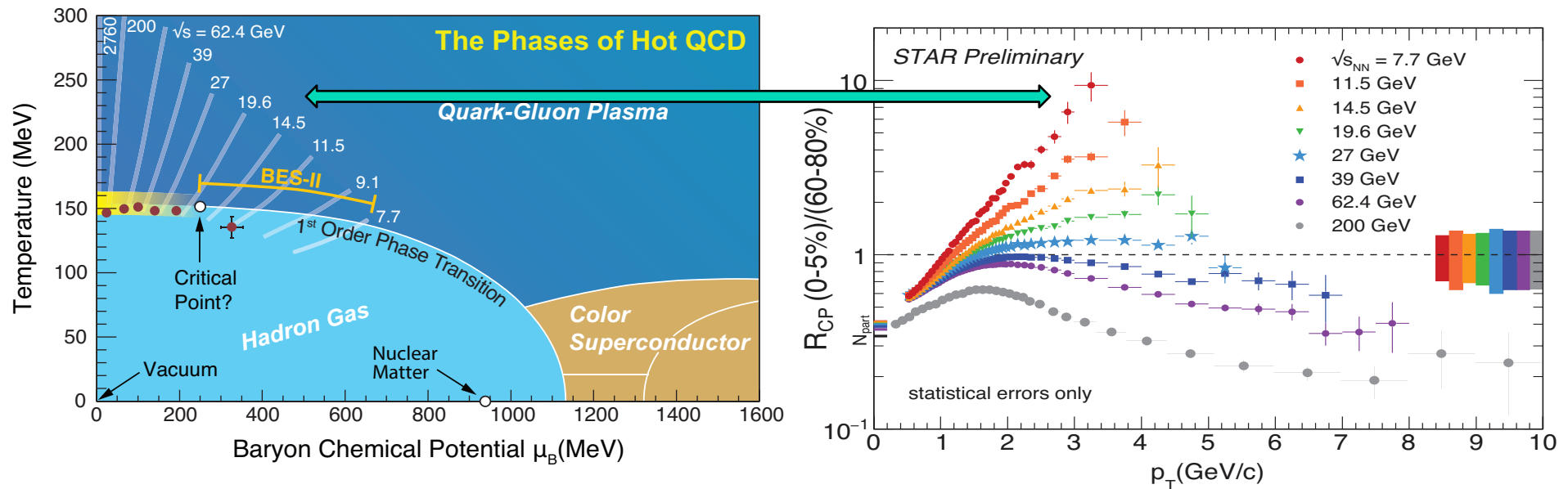
From Bob Tribble, January 17th 2017

- ◆ Update the existing EIC whitepaper science case ... to highlight eRHIC capabilities
- ◆ Contrast the science program at eRHIC to the science program at JLEIC by comparing the
 - a) high profile science capability of each facility,
 - b) discovery science potential of each facility
- ◆ Outline a possible experimental program...for the first 5 years, based on integrated luminosity estimates from C-AD
- ◆ Identify the science community that will benefit directly from EIC work ... provide a plan for engaging them

Outline of presentation: the science case

- ◆ The big picture
- ◆ Basics of DIS: illustration of why reach in both energy and resolution matter for discovery science
- ◆ Novel information on quark & gluon distributions
- ◆ The nucleus as a laboratory of many-body QCD
- ◆ Spin and dynamical three dimensional structure of the proton
- ◆ Additional scientific opportunities
- ◆ The experimental program and deliverables
- ◆ Building a community: EIC science in broader context

Discovery science: Lesson from RHIC



◆ An early measurement strongly hinting at the existence of the QGP was the discovery of “jet” quenching at $\sqrt{s} = 200$ GeV

◆ Because of sufficient p_T reach, $\sqrt{s}=62.4$ GeV might have been sufficient - $\sqrt{s} = 39$ GeV not compelling ❖ ...

Lesson: wide kinematic reach essential to QGP discovery

❖ lower energy heavy-ion colliders were proposed at the same time. VENUS at LBL at $\sqrt{s}=27$ GeV and the ISR at CERN at comparably low energy. Neither would have unambiguously discovered the QGP

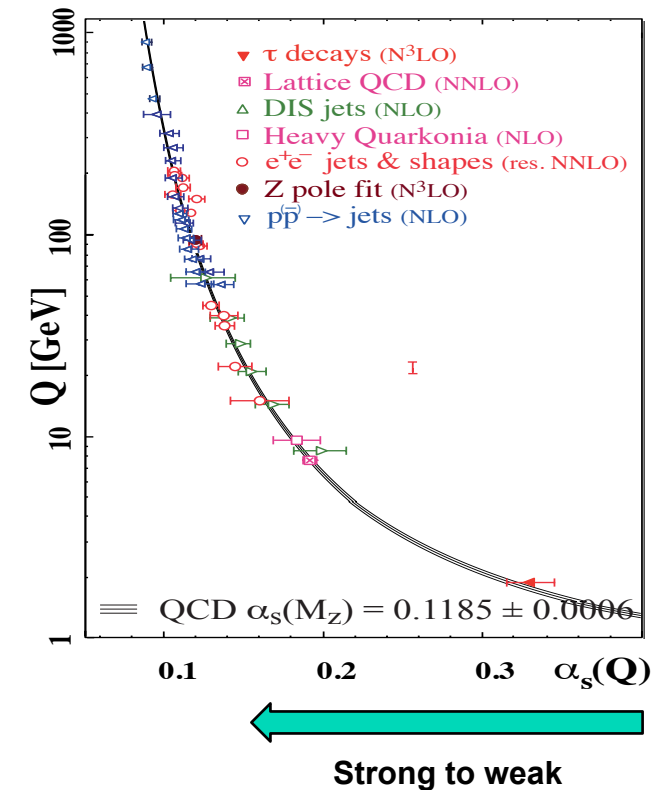
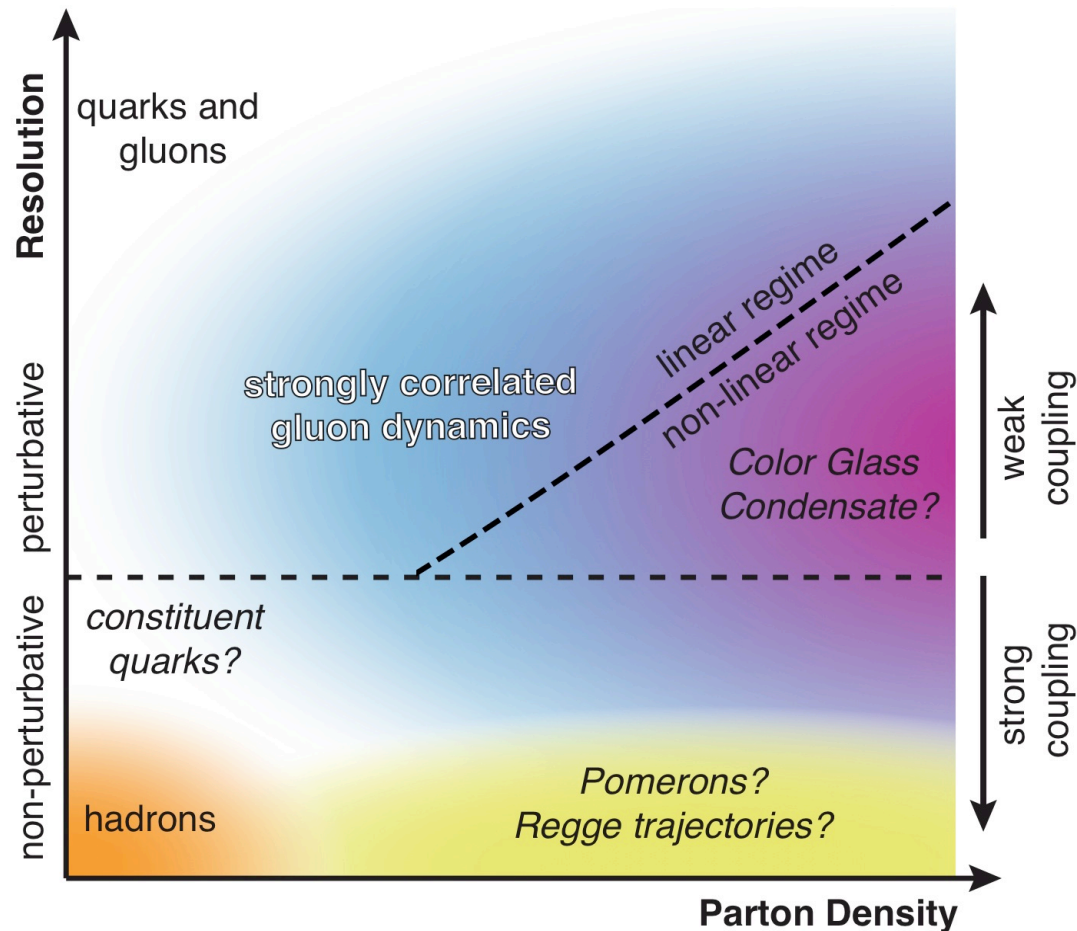
The strong interaction landscape

- ◆ QCD is the universally accepted theory of the strong interaction

- ◆ This is due to
 - a) the great success of perturbative QCD in describing a very wide range of high resolution processes

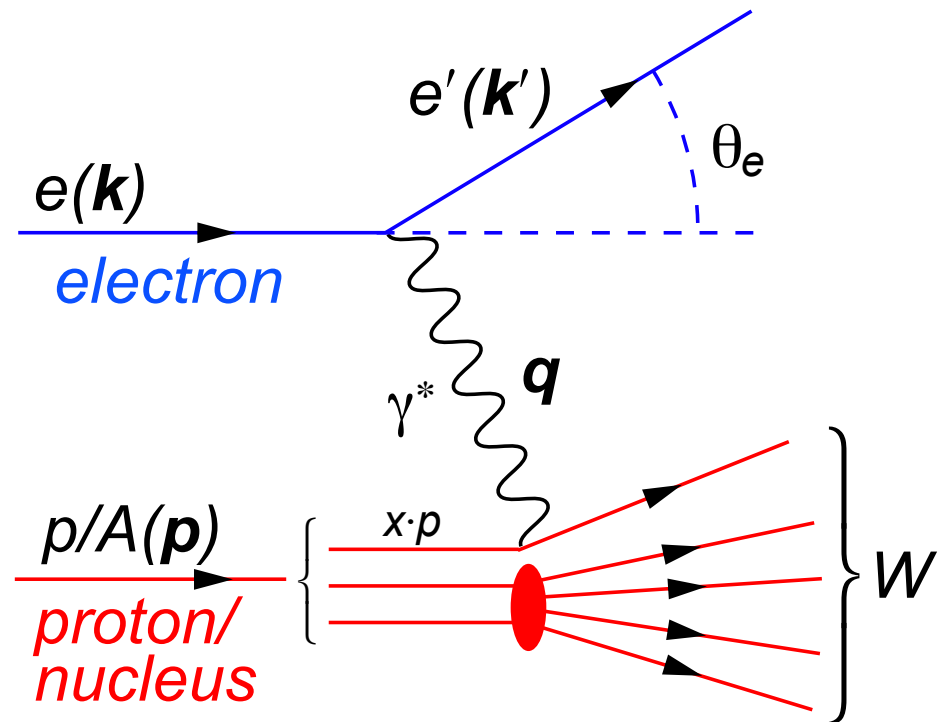
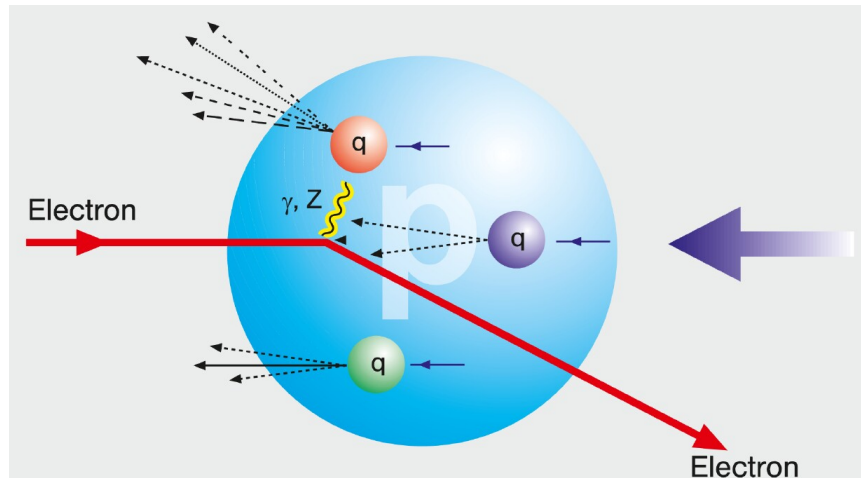
 - b) the increasingly precise description of the spectrum of hadrons by lattice QCD

The strong interaction landscape



While quarks and gluons (partons) anchor one corner of this landscape, and hadrons another, our knowledge of the dynamics of the rest is fragile

Deeply inelastic scattering



s: center-of-mass energy squared

Q^2 : resolution power of probe

x: fraction of the nucleon's momentum carried by the struck quark ($0 < x < 1$)

y: inelasticity ($0 < y < 1$)

Simple mnemonic

$$Q^2 \approx s \cdot x \cdot y$$

Frontiers of our ignorance:

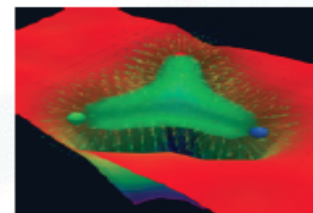
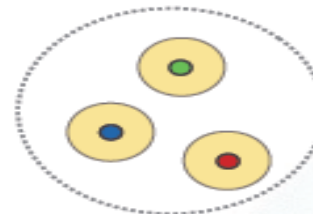
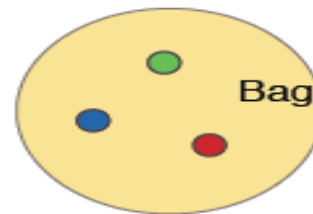
Matter below the femto scale: 3-D structure of confined partons

➤ What EIC brings to the game:
precise 3-D spatial & mom. space
images of many-body dynamics
of unpolarized and polarized
quarks and gluons

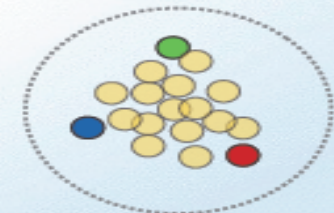
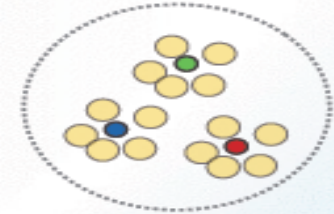
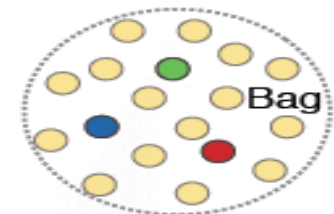
◆ Vast leap in understanding of
polarized gluon and orbital motion

◆ Fundamental progress in
understanding the dynamics of
confinement and chiral symmetry breaking?

Static pictures



Glue dominated
boosted proton



Frontiers of our ignorance: II

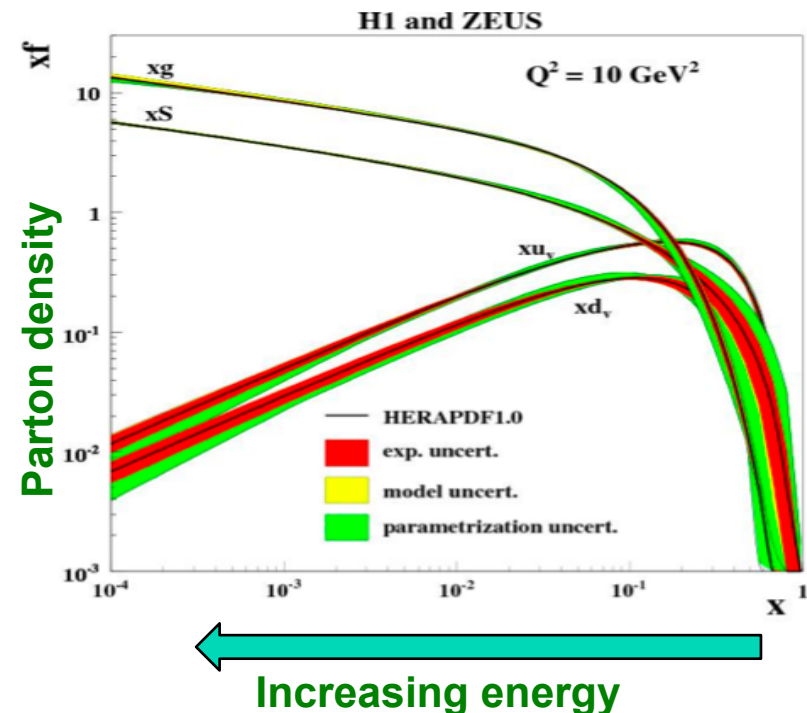
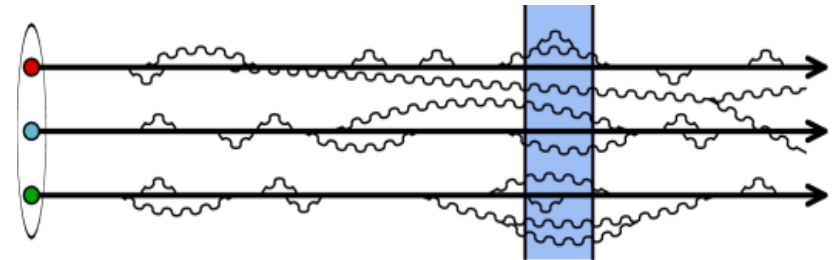
Many-body gluodynamics of matter at high energies ?

◆ The structure of high energy cross-sections is mysterious.
Remarkable color singlet exchange patterns (pomeron, reggeons)
...fundamental understanding elusive

◆ A role for vacuum structures such as instantons? Do conformal and chiral anomalies influence dynamics?

➤ What EIC brings to the game:
powerful tools of spin-dependent diffractive and exclusive DIS

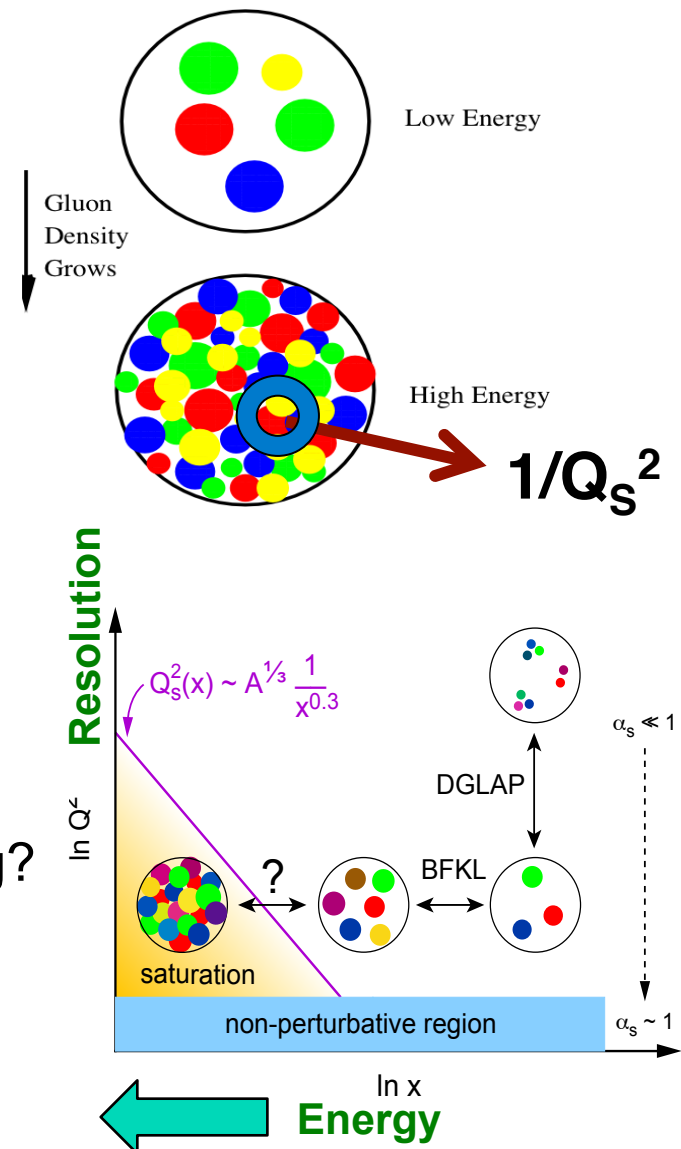
Boosted protons lift the veil hiding glue



Frontiers of our ignorance: III

Universal saturated gluon matter: a Color Glass Condensate?

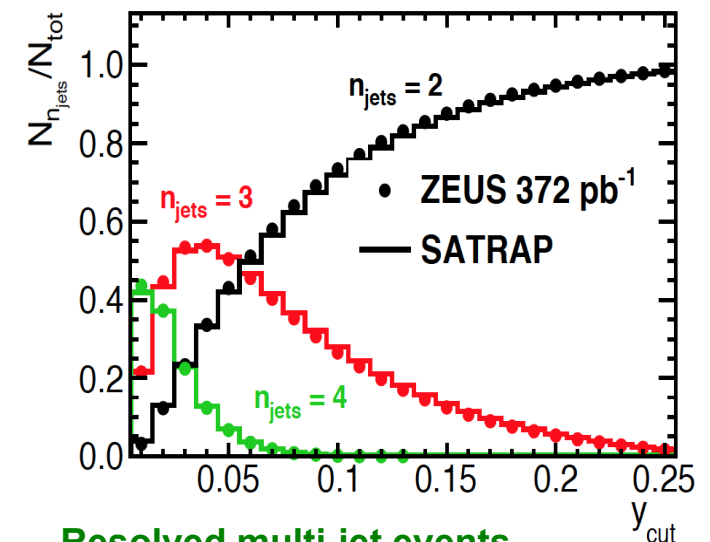
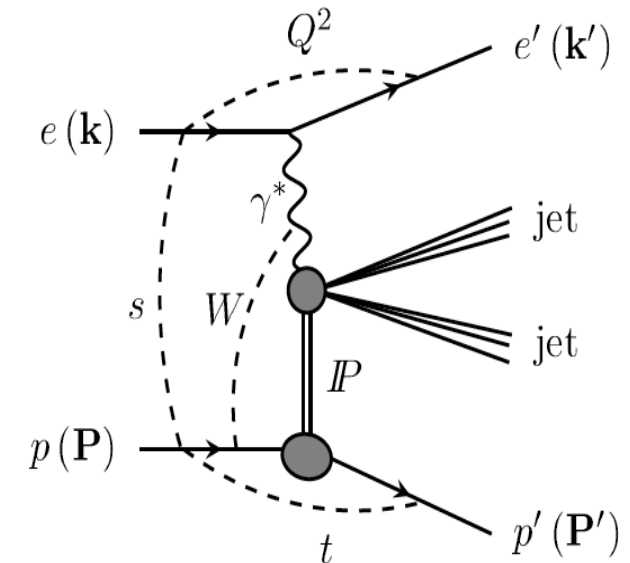
- ◆ How does the exploding population of gluons saturate?
- ◆ Color Glass Condensate (CGC)
 - weakly coupled, strongly correlated, gluons
 - emergent scale Q_s grows with energy and nuclear size
- ◆ Does the QCD coupling run with Q_s ?
Other emergent scales?
- ◆ Deep connection of CGC strong color fields to those from confinement/chiral symmetry breaking?
- What EIC brings to the game: strong discovery potential with unique measurements



Frontiers of our ignorance: IV

How do partons form hadrons in vacuum and in matter?

- ◆ Can we use nuclei as filters to study hadron formation in and out of colored media?
- ◆ Can we definitively elucidate mechanisms of parton energy loss in cold nuclear matter? Are there novel quantum entanglement effects?
- What EIC brings to the game:
first DIS studies of formation of charm and bottom mesons and baryons in nuclei
- first DIS studies of jets and jet showers in media



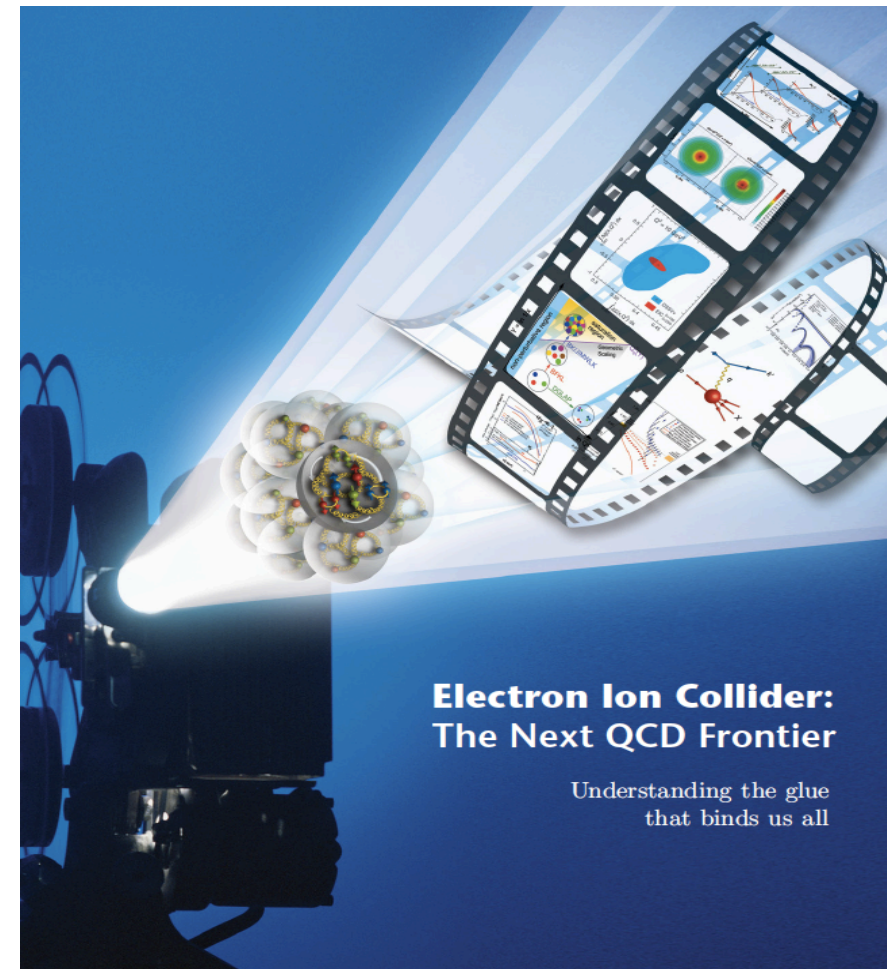
Resolved multi-jet events
from HERA: [arXiv:1505.05783](https://arxiv.org/abs/1505.05783)

The EIC whitepapers

INT Report on EIC Science

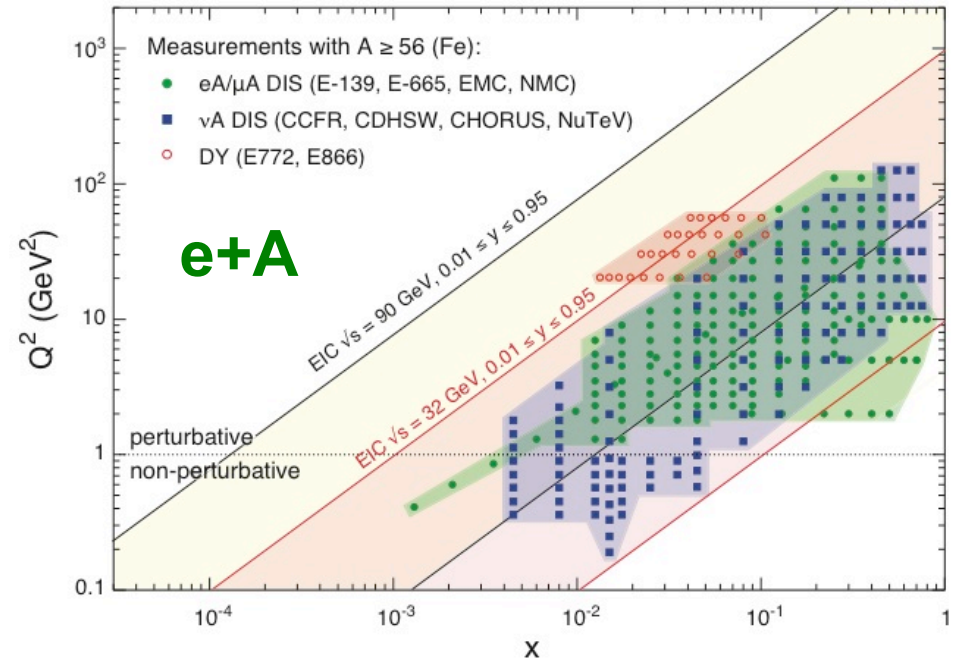
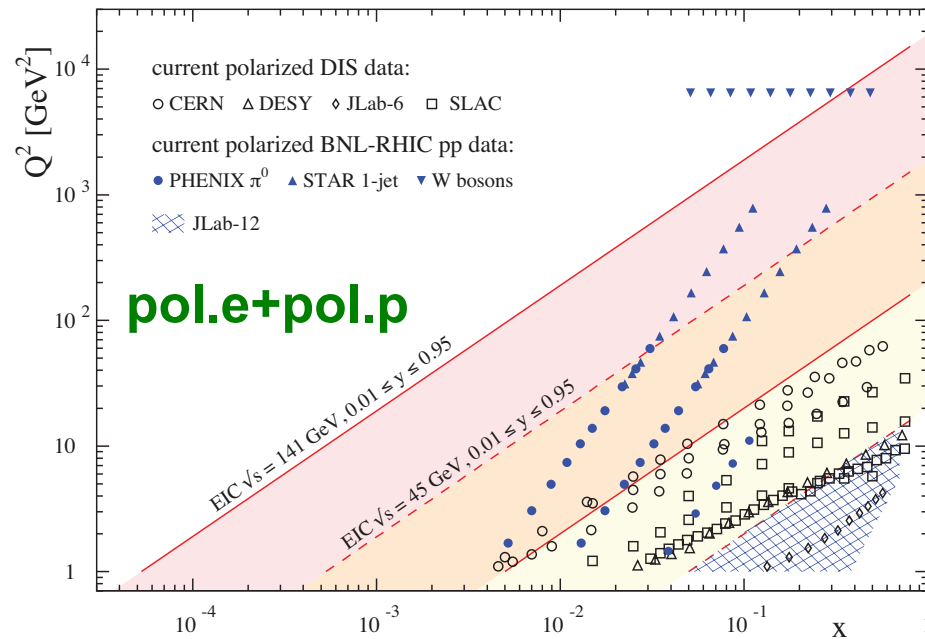


arXiv:1108.1713, cited 356 times



Eur. Phys. J. A52 (2016),no. 9,268
cited 318 times

eRHIC kinematic reach



eRHIC

JLEIC

e+p: $\sqrt{s}_{\max} = 140$

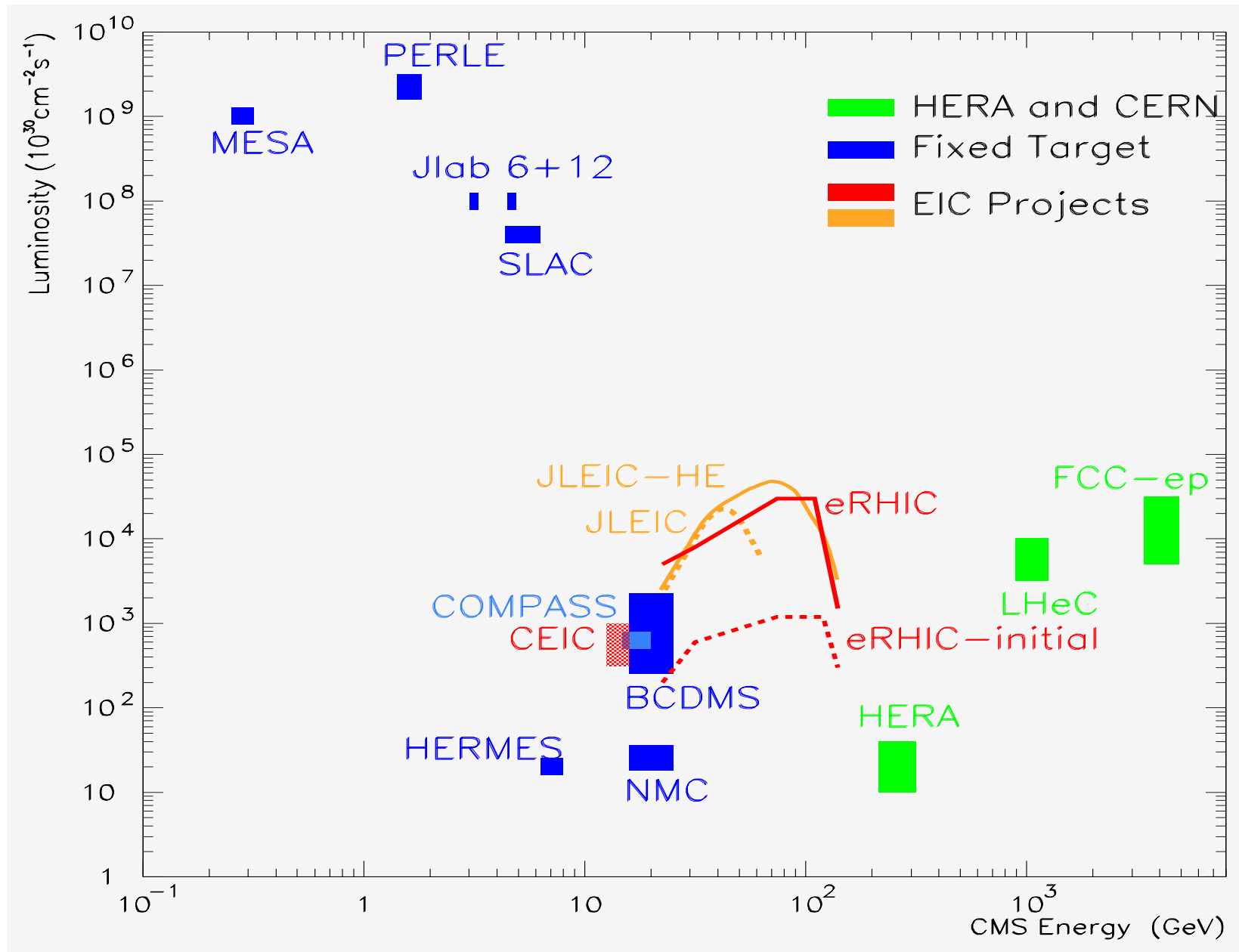
e+Au: $\sqrt{s}_{\max} = 90$

e+p: $\sqrt{s}_{\max} = 63$

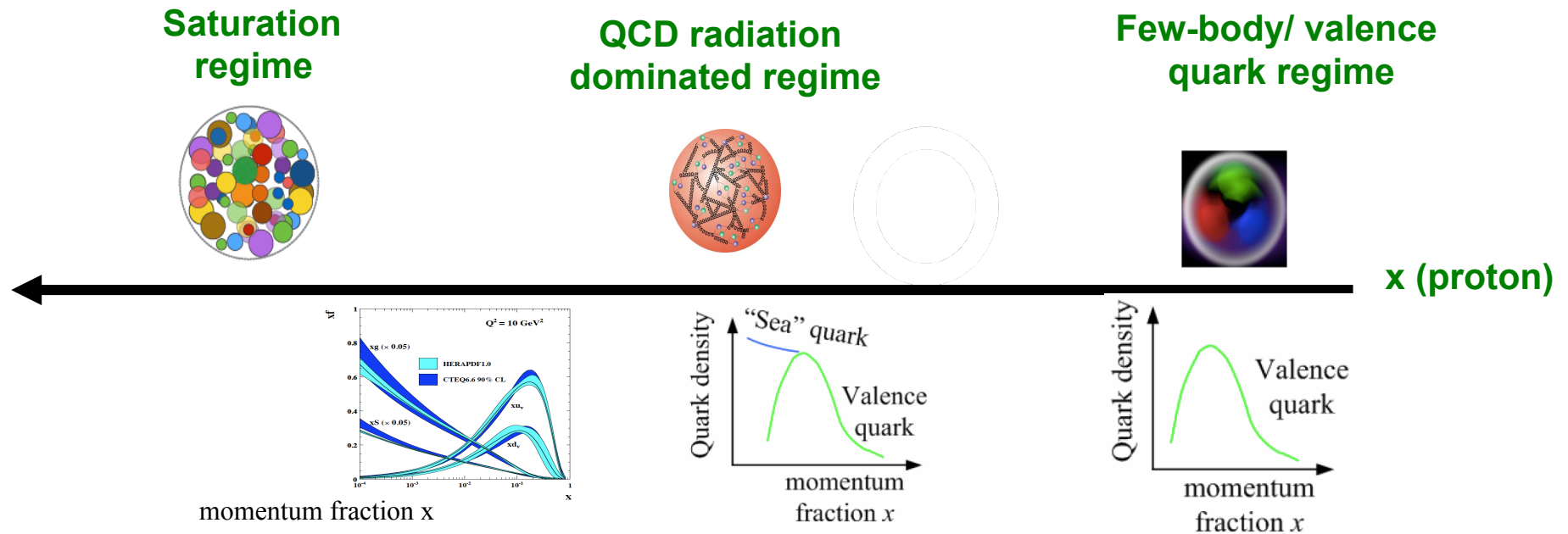
e+Au: $\sqrt{s}_{\max} = 40$

nuclei from Deuterium to Uranium

eRHIC luminosity



eRHIC science: energy, polarization, luminosity



Large center-of-mass coverage: access to wide range in x and Q^2

Polarized electron and hadron beams:

access to spin structure of nucleons and nuclei

Spin vehicle to access 3D spatial and momentum structure of the nucleon

Nuclear beams:

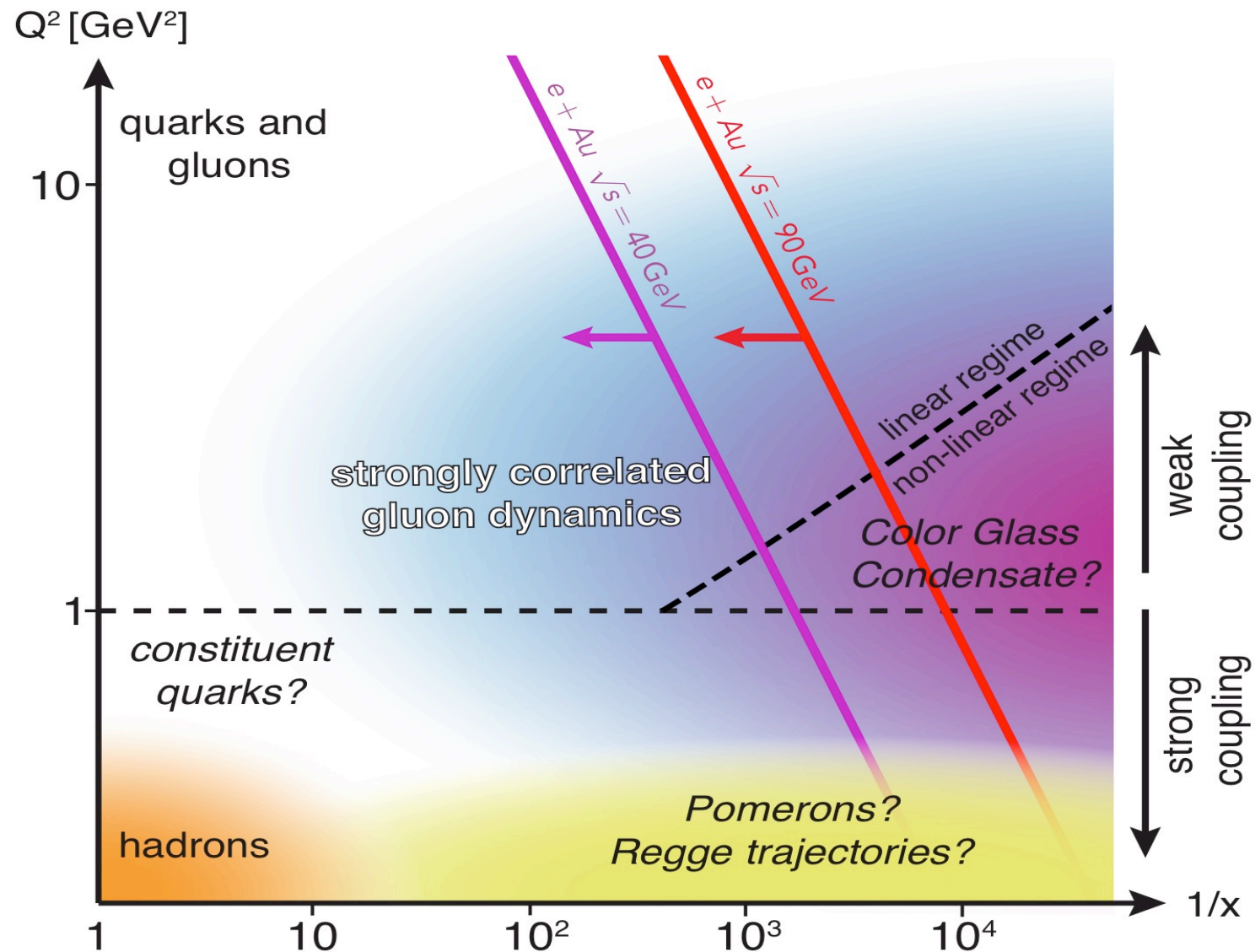
accessing the highest gluon densities

High luminosity:

essential for mapping 3D structure of nucleons and nuclei

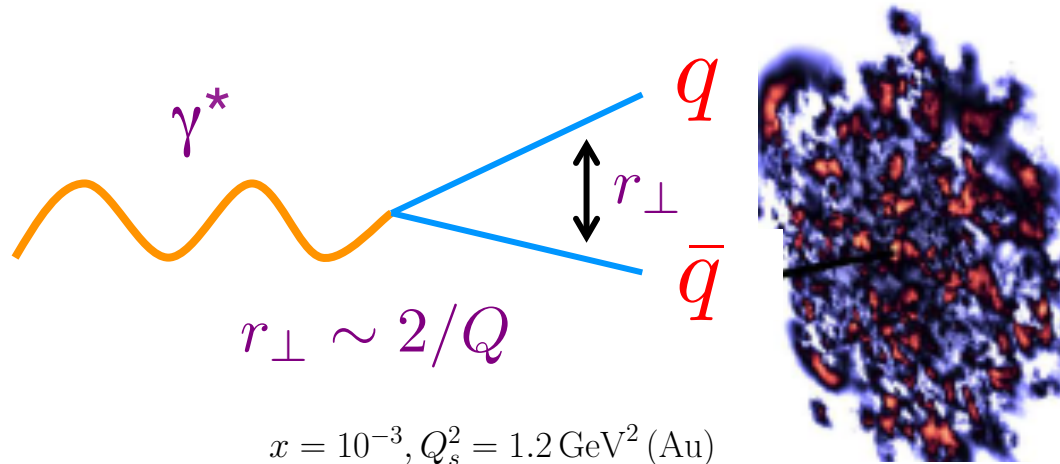
access to rare probes

eRHIC: precision probe of QCD landscape

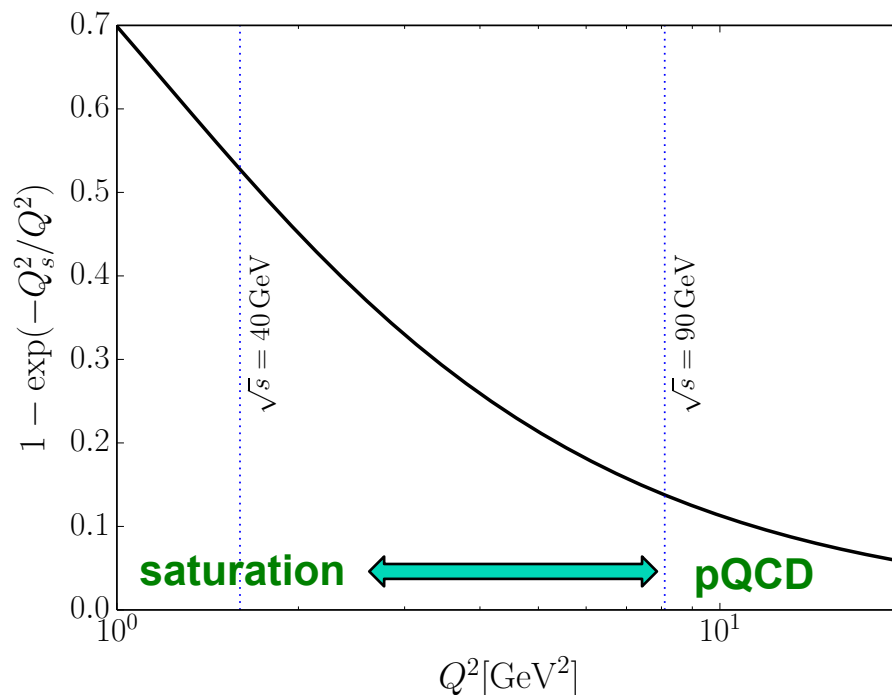


Simple illustration of the eRHIC advantage

The dipole paradigm at high energies



Virtual photon “splits” into a quark-antiquark dipole
– fine femtoscope of color fields inside hadrons and nuclei



$$\sigma_{q\bar{q}P} \approx \sigma_{\text{hadron}} \left[1 - \exp \left(-Q_s^2(x)/Q^2 \right) \right]$$

$$Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x} \right)^\lambda$$

Parameters: $Q_0 = 1 \text{ GeV}$; $\lambda = 0.3$;

$x_0 = 3 \cdot 10^{-4}$; $\sigma_{\text{hadron}} = 23 \text{ mb}$

Though $Q_s^2(x)$ varies slowly with energy, the additional factor 5 in Q^2 reach of eRHIC relative to JLEIC is significant...

The glue that binds us all

On display in the Paris metro in September 2015 ...



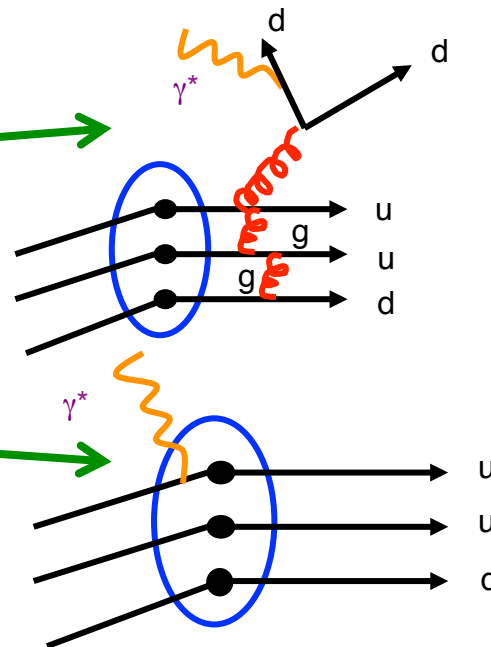
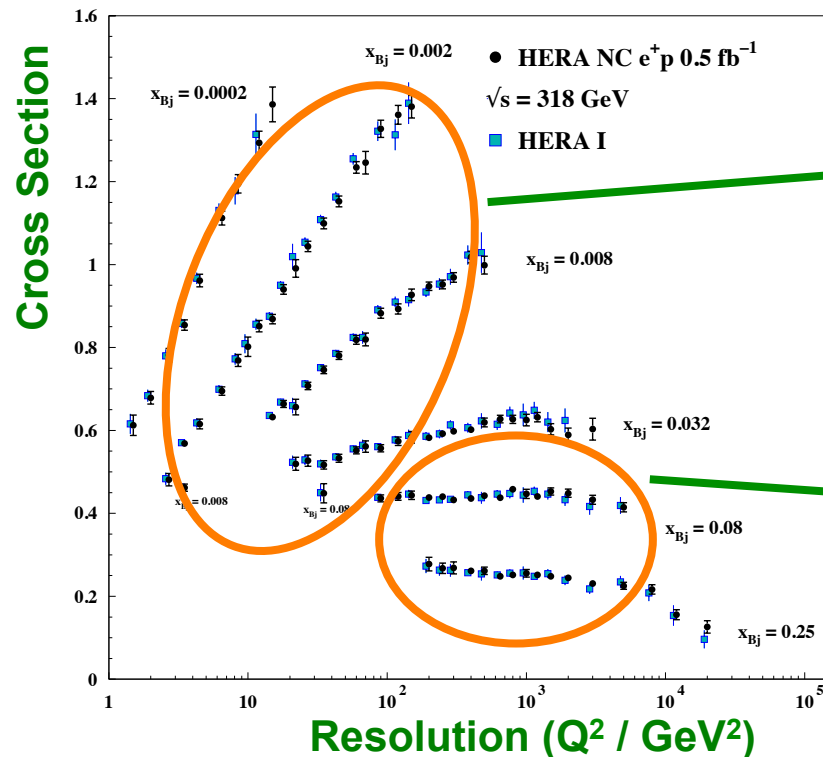
Scientific American
May 2015



How does DIS access glue? Scaling violations

$$\frac{d^2\sigma^{ep\rightarrow eX}}{dx dQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4} \left[\left(1 - y + \frac{y^2}{2}\right) \underset{\substack{\uparrow \\ \text{quark+anti-quark} \\ \text{momentum distributions}}}{F_2(x, Q^2)} - \frac{y^2}{2} \underset{\substack{\uparrow \\ \text{gluon momentum} \\ \text{distribution}}}{F_L(x, Q^2)} \right]$$

◆ Without gluons, these cross-sections would only depend on x



Glue from scaling violations:
 $dF_2 / d \ln(Q^2)$

Bjorken scaling
-quasi-free quarks

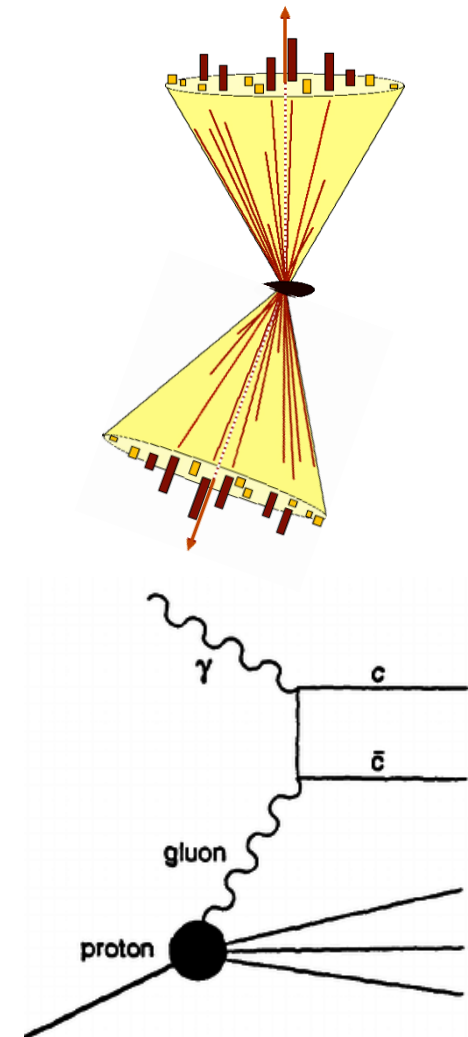
Accessing glue: F_L and photon-gluon fusion

◆ Measuring F_L by varying the DIS center-of-mass energy, provides an independent method to extract gluons

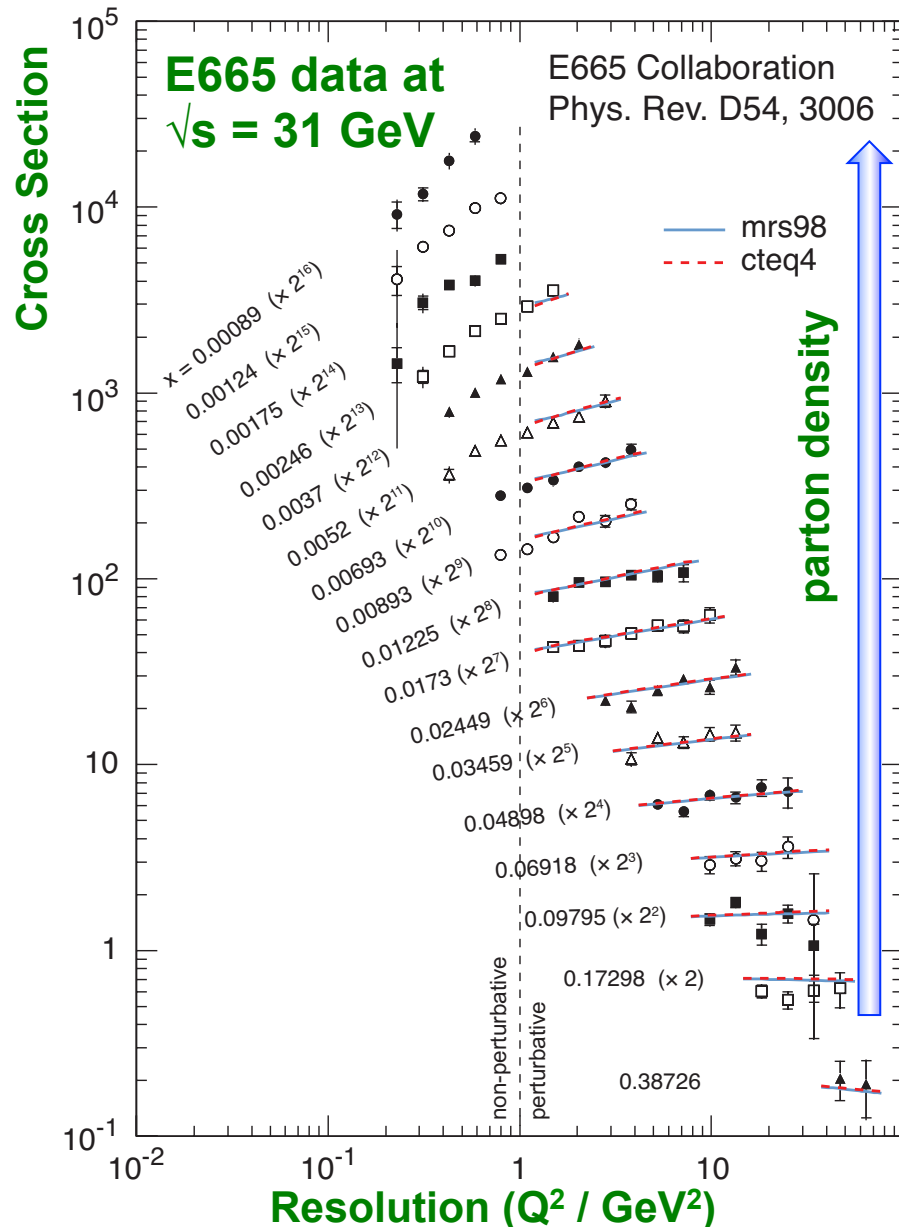
◆ Tagging of the photon-gluon fusion process via di-jets

production of charm quarks

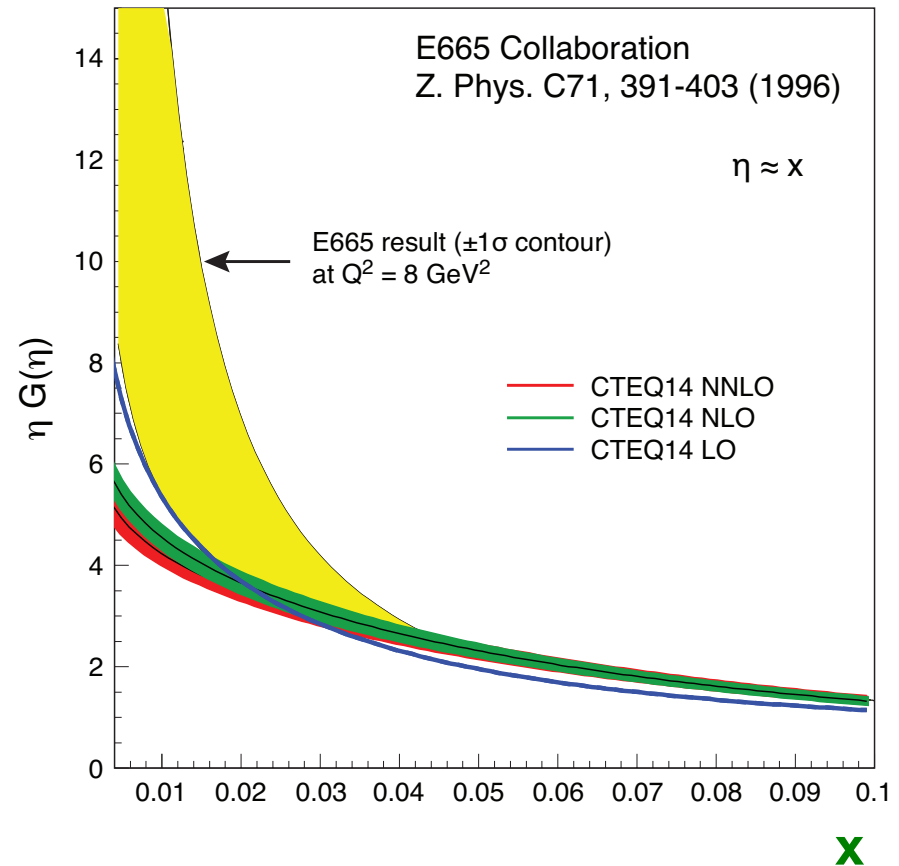
◆ Wide coverage in x and Q^2



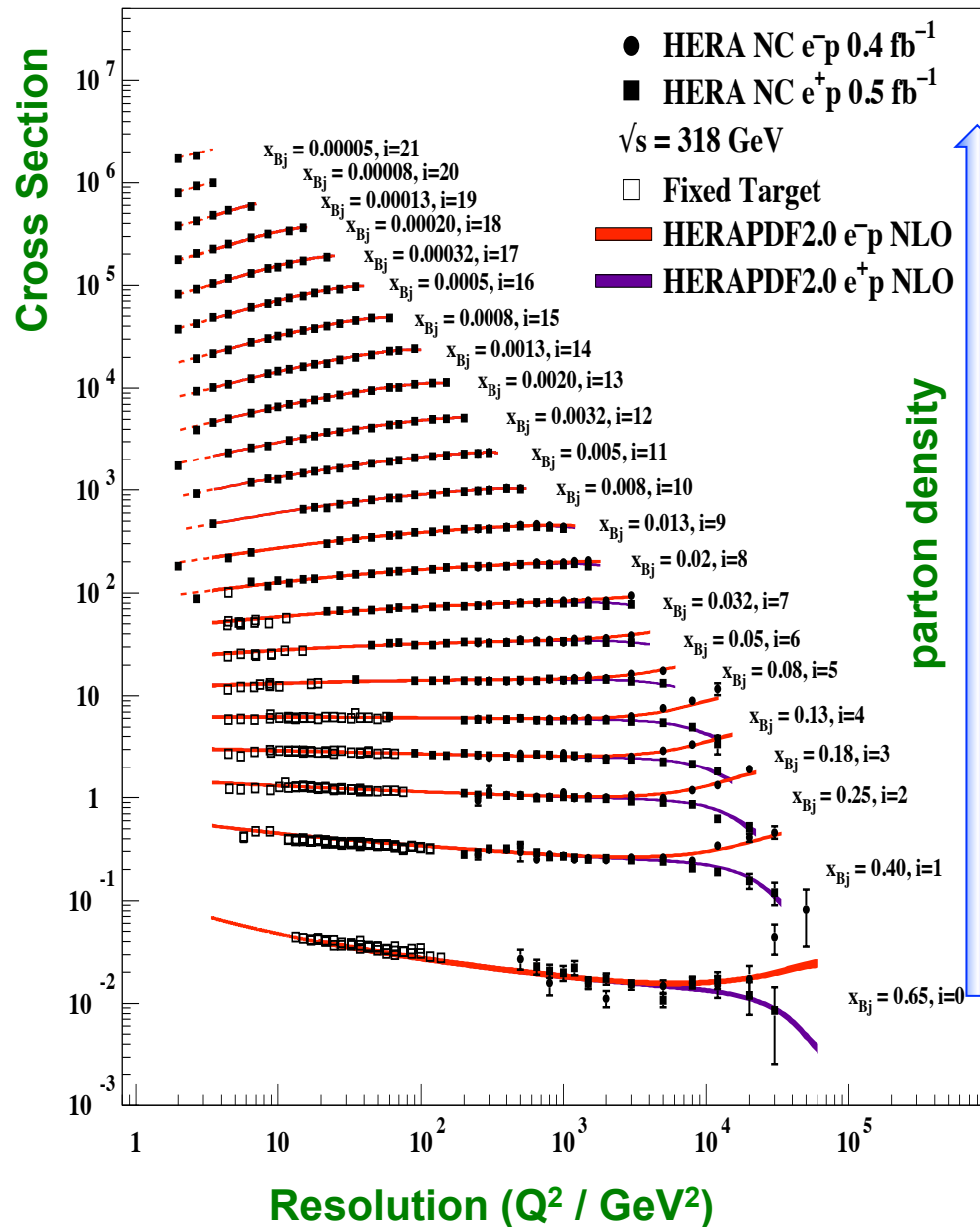
Extracting glue: the c.m energy matters



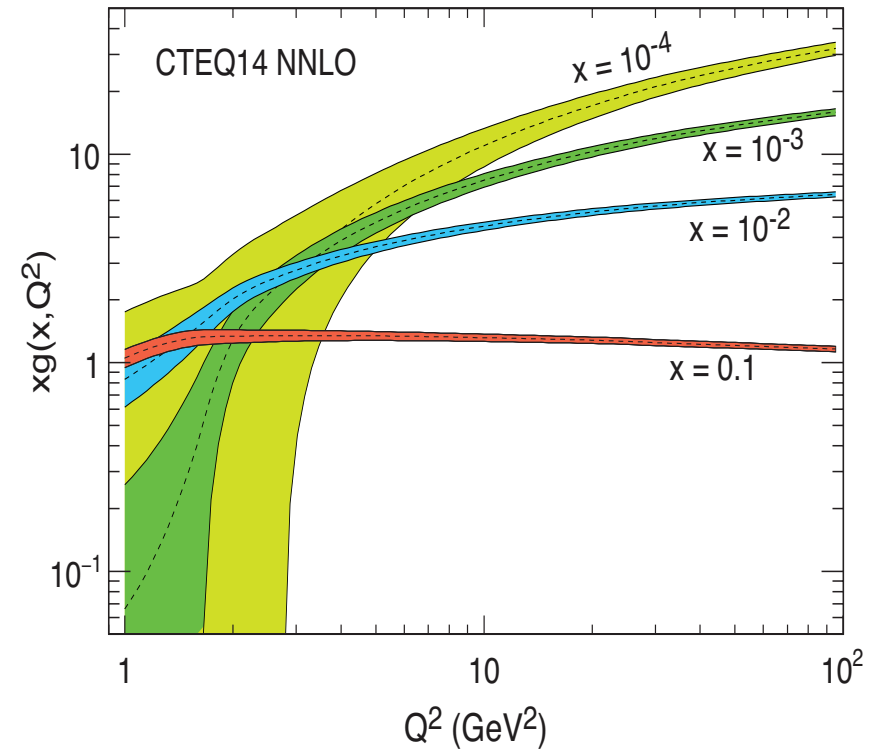
- ♦ Lack of kinematic coverage and lever arm limits the accuracy
- ♦ Rise with decreasing x strongly overestimated



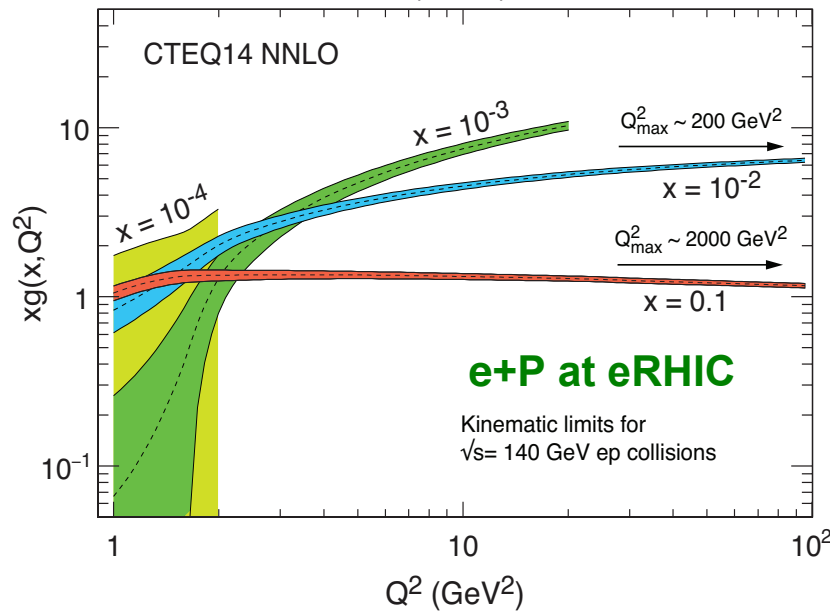
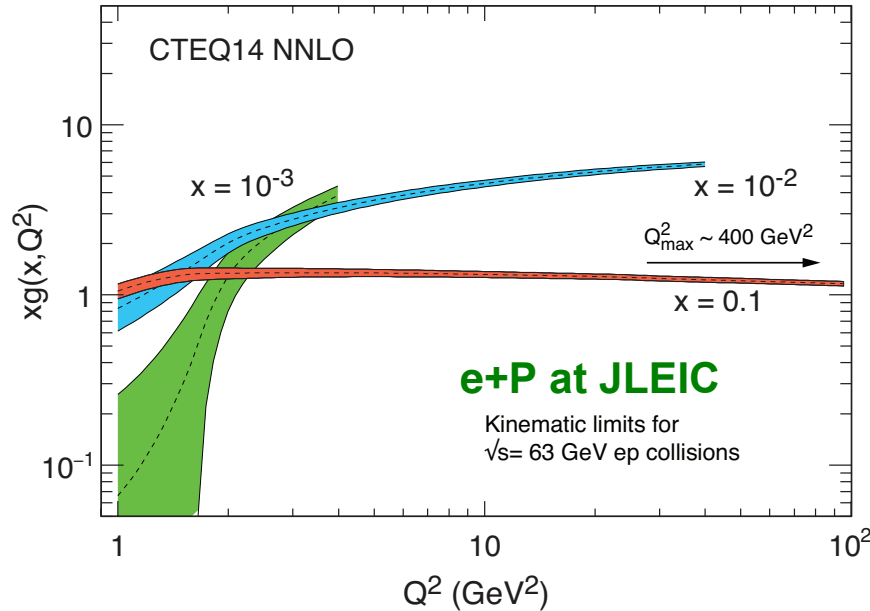
Extracting glue: the c.m energy matters



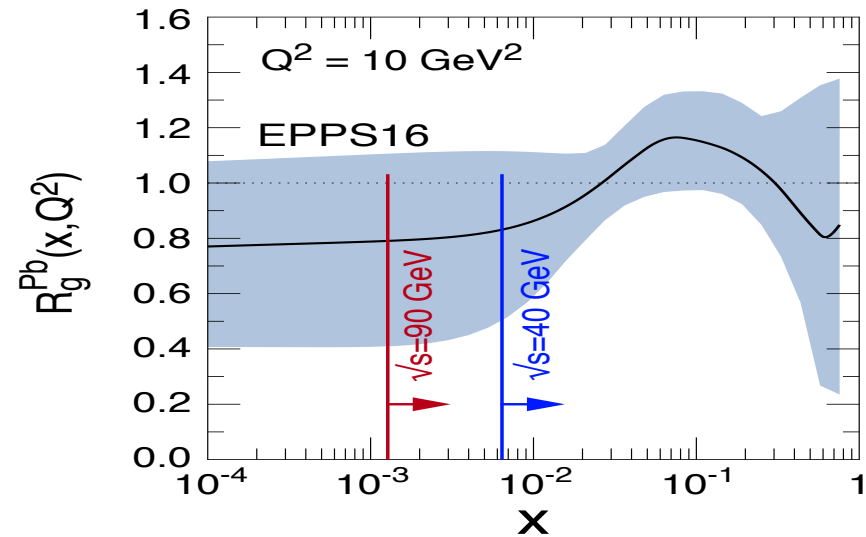
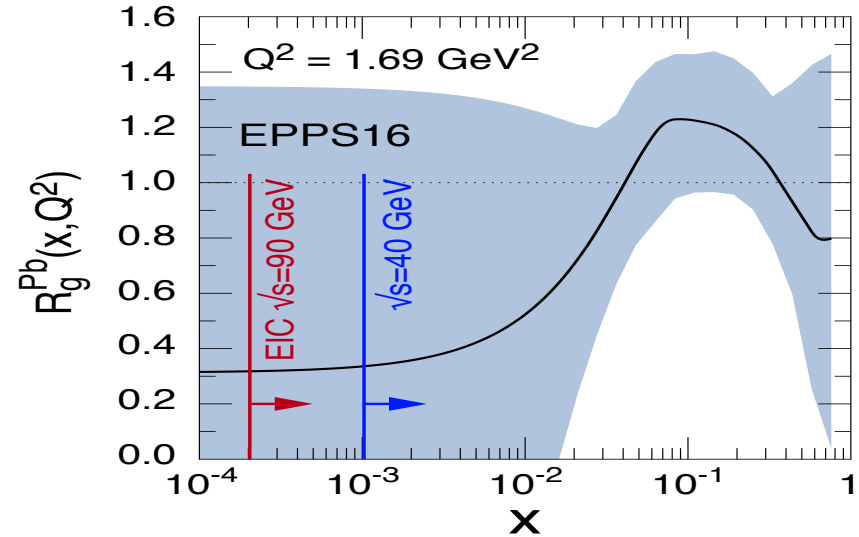
◆ The rise of the cross section as function of Q^2 at low x is directly reflected in the gluon distribution



EIC kinematic reach and the gluon distribution



Normalized ratio of nuclear to proton gluon pdfs



Beyond the whitepaper



Small sampling of recent developments:

1. Deep inelastic scattering as a probe of entanglement.

Dmitri Kharzeev, Eugene Levin, arXiv:1702.03489

2. Evidence of strong proton shape fluctuations from incoherent diffraction.

Heikki Mäntysaari, Björn Schenke **Phys.Rev.Lett. 117 (2016) no.5, 052301**

3. Probing short-range nucleon-nucleon interactions with an Electron-Ion Collider.

Jerry Miller, Matt Sievert, Raju Venugopalan, **Phys. Rev. C93 (2016) no.4, 045202**

4. Distribution of Linearly Polarized Gluons and Elliptic Azimuthal Anisotropy in Deep Inelastic Scattering Dijet Production at High Energy.

Adrian Dumitru, Tuomas Lappi, Vladimir Skokov
Phys.Rev.Lett. 115 (2015) no.25, 252301

5. Ballistic protons in incoherent exclusive vector meson production as a measure of rare parton fluctuations at an Electron-Ion Collider.

Tuomas Lappi, Heikki Mäntysaari, Raju Venugopalan
Phys.Rev.Lett. 114 (2015) no.8, 082301